Adam, Clayton J. and Askin, Geoffrey N. (2006) Automatic measurements of vertebral rotation in idiopathic scoliosis. *Spine : An international journal for the study of the spine* 31(3):E80-E83.

Automatic measurement of vertebral rotation in idiopathic scoliosis.

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Sources of Support

No financial support was received for this study

Acknowledgements

The authors wish to acknowledge the contribution of M. Izatt and J. Doocey who performed rotation measurements in this study.

Mini Abstract

Vertebral rotation is an important feature of spinal deformity in idiopathic scoliosis. An algorithm has been developed for automatic measurement of vertebral rotation from computed tomography scans with no observer variability. Comparison with manual measurements shows that the algorithm has insignificant bias compared to either Aaro or Ho’s methods.

Abstract

Study Design: Development of an automatic measurement algorithm and comparison with manual measurement methods. **Objectives:** To develop a new computer-based method for automatic measurement of vertebral rotation in idiopathic scoliosis from computed tomography images, and to compare the automatic method with two manual measurement techniques. **Summary of Background Data:** Techniques have been developed for vertebral rotation measurement in idiopathic scoliosis using plain radiographs, computed tomography, or magnetic resonance images. All of these techniques require manual selection of landmark points and are therefore subject to inter and intra-observer error. **Methods:** We develop a new method for automatic measurement of vertebral rotation in idiopathic scoliosis using a symmetry ratio algorithm. The automatic method provided values comparable with Aaro and Ho's manual measurement methods for a set of 19 transverse computed tomography slices through apical vertebrae, and with Aaro's method for a set of 204 reformatted computed tomography images through vertebral endplates. **Results**: 95% confidence intervals for intra and inter-observer variability using manual methods were in the range 5.5-7.2°. The mean (±SD) difference between automatic and manual rotation measurements for the 19 apical images was -0.5 ± 3.3° for Aaro's method, and 0.7 ± 3.4° for Ho's method. The mean (±SD) difference between automatic and manual rotation measurements for the 204 endplate images was 0.25 ± 3.8°. **Conclusions**: the symmetry ratio algorithm allows automatic measurement of vertebral rotation in idiopathic scoliosis without intra or inter-observer error due to landmark point selection.

Keywords

Vertebral rotation, idiopathic scoliosis, automatic measurement, computed tomography, symmetry ratio algorithm

Key Points

1. A new method is presented for automatic measurement of vertebral rotation in idiopathic scoliosis

2. The method uses a symmetry ratio algorithm to measure rotation from CT images

3. Automatic rotation measurements are not subject to intra and inter-observer error due to landmark point selection

4. The automatic rotation measurement method has insignificant bias compared with either Aaro or Ho’s manual measurement techniques

Introduction

Vertebral rotation is an important feature of spinal deformity in idiopathic scoliosis (Fig 1a). Various techniques have been developed to assess vertebral rotation[1-17], however existing techniques require user selection of landmark points and are therefore subject to inter and intra-observer errors. This paper presents a new computerized method for automatic measurement of vertebral rotation in idiopathic scoliosis without the need for manual landmark selection.

Materials and Methods

The *symmetry ratio algorithm* is based on the premise that the axis of maximum symmetry of a vertebral cross-section also defines the angular orientation of the vertebra.

Symmetry ratio algorithm

Once a digital image has been obtained and the region of interest defined, the symmetry ratio algorithm performs automatic measurement of vertebral rotation as follows; (i) thresholding (Fig 1b) is performed according to pre-defined levels, (ii) centroid location is calculated for black pixels in the image, (iii) a ‘reflection axis’ passing through the centroid is defined at a known angle to the vertical. Black pixels on one side of the axis are then ‘reflected’ to their corresponding location on the other side of the axis to assess the symmetry of reflection of the object about the axis (Figure 2). If a black pixel is found at the reflected location, a successful mapping is recorded. If a white pixel is found, an unsuccessful mapping is recorded. This procedure is repeated for all black pixels on the control side of the reflection axis. The symmetry ratio S_r is defined as

$$S_r = \frac{n_p}{n_T}$$

Where n_p is the number of pixels successfully mapped across the reflection axis, and n_T is the total number of black pixels on the control side of the reflection axis. The symmetry ratio for the simple case in Figure 2 would be 0.50, since 2 of the 4 black pixels mapped successfully across the reflection axis. (iv) Symmetry ratio is calculated for a series of reflection lines passing through the centroid of the image at incrementally (0.1°) increasing angles. The angle at which the symmetry ratio S_r reaches a maximum is determined, and this angle corresponds to the angle of rotation of the vertebra. This process is shown schematically in Figure 3 where the centroid of an object is located (Fig 3b), a successful and unsuccessful mapping across an arbitrary reflection line are shown (Fig 3c), and the reflection line of maximum symmetry ratio gives the angle of rotation of the object (Fig 3d). The variation in symmetry ratio with reflection line angle for an actual vertebra is shown in Figure 4. The peak corresponding to maximum symmetry ratio can be clearly seen at a rotation of 20.8° to the vertical.

Comparison with manual measurements

The algorithm was implemented as an automated Java plug-in for the *ImageJ* image processing software (version 1.33, National Institutes of Health, USA) and is available on request from the authors. The new method was assessed by comparing symmetry ratio rotation measurements with manual measurements for two sets of CT images of idiopathic scoliosis patients:

Set A: 19 transverse CT slices through apical vertebrae at mid-vertebral body

Set B: 204 reformatted CT slices through thoracolumbar vertebral endplates

Reformatted images were used in Set B to avoid angulation errors associated with rotation measurements using transverse slices[13,17,18-20]. Each Set A image was measured using; (a) Aaro's method[10], (b) Ho's method[12], and (c) the symmetry ratio algorithm. Set B images were similarly measured, however Ho's method was not used since the junction between the laminas and pedicles is often not visible on reformatted slices through the plane of the superior endplate. Each manual measurement was repeated by three observers on three occasions for a total of nine manual measurements per image.

Statistical analysis

Automatic and manual measurements were compared using the approach of Bland & Altman[21]. 95% confidence intervals were calculated using normal distribution theory and $\sqrt{2}\times$SD was used to calculate the standard deviation of inter-observer variability. Mean and standard deviation of absolute difference between manual and automatic measurements was determined, and correlation coefficients were calculated for manual versus automated rotation measurements.

Results

Set A measurements

Table 1 gives mean measurements for the two manual techniques and automatic (symmetry ratio) rotations in each of the 19 patients. For the apical images in Set A, overall 95% confidence intervals for intra and inter-observer variability using Aaro's method were ±5.5° ($1.96\times SD$) and ±7.2° ($\sqrt{2}\times1.96\times SD$) respectively. Confidence intervals for the same images using Ho's method were ±6.4° (intra) and ±6.7° (inter).

The difference between manual and automatic (symmetry ratio) rotation measurements was calculated for each image as R_{sym} - R_{man}, where R_{sym} is the rotation angle measured automatically and R_{man} is the manual measurement. The overall mean difference between Aaro's method and the symmetry ratio algorithm for Set A was -0.5° and standard deviation of differences was 3.3°. For Ho's method, the overall mean difference was 0.7° and standard deviation of differences was 3.4°.

Assuming that the mean of the nine manual observations for each image in Set A represents a 'true' rotation measurement, the standard deviation of differences between automatic and 'true' (mean manual) rotation was 2.3° for Aaro's method and 2.6° for Ho's method. Correlation between symmetry ratio and mean manual rotations for Set A was R^2=0.71 for Ho's method and R^2=0.81 for Aaro's method.

Set B measurements

Table 2 gives mean manual and automatic (symmetry ratio) rotations in all thoracolumbar endplates for one patient in Set B. For the entire 204 images in Set B, overall 95% confidence intervals for intra and inter-observer variability using Aaro's method were ±5.8° (1.96×*SD*) and ±6.8° (√2×1.96×*SD*) respectively.

The overall mean difference between manual and automatic (symmetry ratio) rotation measurements for Set B was 0.25° and standard deviation of differences was 3.8°. Again assuming that the mean of the nine manual observations for each image in Set B represents a 'true' rotation measurement, the mean difference between symmetry ratio and 'true' rotation was -1.4°, and standard deviation of differences from the mean was 2.7°. The correlation between symmetry ratio and mean manual rotations for Set B was R^2=0.90. The spinal region being measured (thoracic or lumbar) did not significantly alter the difference between the symmetry ratio and ‘true’ (mean manual) rotation measurements in Set B.

Effect of thresholding

The automatic measurement method is relatively insensitive to changes in threshold grey level. Figure 5 shows the effect of changes in threshold grey level on rotation angle measured using the symmetry ratio algorithm. For a typical 8-bit image (256 shades of grey), changing the threshold grey level over a wide range (150-250, 39% of full scale) resulted in a 2.8° maximum variation in measured rotation angle.

Discussion

The mean difference between manual and automatic methods R_{sym} - R_{man} was not significantly different from zero for either Set A or Set B, indicating that the symmetry ratio algorithm may be used interchangeably with either Aaro or Ho’s methods with negligible bias. Standard deviations of difference between automatic and mean manual measurement suggest that although the symmetry ratio algorithm measures the same rotation angle as the manual techniques on average, in individual cases the rotation angles derived from symmetry ratios may vary by up to ±6.7° from the values defined by selection of landmark points in Aaro’s method (95% confidence interval of 1.96×SD).

Defining the region of interest for the symmetry ratio algorithm can be problematic in some thoracic images, as the interface between transverse processes and rib heads may not be clearly defined, requiring manual removal of the rib heads from the image which introduces another source of observer variability.

Although radiation doses currently preclude sequential CT scans, a single pre-operative CT scan is currently clinically indicated for endoscopic scoliosis surgery planning[22], and the symmetry ratio algorithm allows measurements of intravertebral (within the bone), and overall rotation for these patients without observer variability due to landmark point selection.

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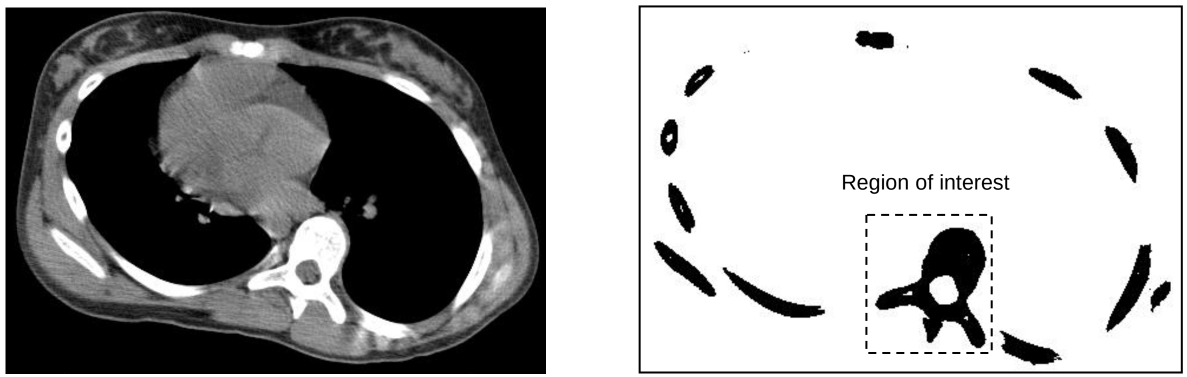
Table 1. Vertebral rotation measurements (Set A)

Patient	Aaro	Ho	Symmetry angle	Symmetry ratio (S_r)
	Mean(SD) (n=9)			
1	23.9(2.1)°	23.0(3.0)°	22.6°	0.74
2	14.4(3.1)°	13.7(2.5)°	12.2°	0.74
3	18.7(4.0)°	14.6(1.9)°	16.2°	0.76
4	14.5(2.3)°	12.9(2.6)°	11.0°	0.71
5	13.8(1.8)°	14.7(1.6)°	15.4°	0.72
6	4.7(1.8)°	5.1(1.4)°	6.2°	0.73
7	2.1(1.2)°	5.5(2.8)°	6.2°	0.74
8	17.1(2.6)°	12.4(2.8)°	14.6°	0.67
9	20.9(1.7)°	23.2(2.1)°	20.8°	0.78
10	10.3(1.9)°	12.6(1.5)°	8.0°	0.62
11	15.1(3.5)°	16.0(2.5)°	14.4°	0.73
12	22.7(3.2)°	16.0(2.1)°	21.2°	0.74
13	13.8(2.4)°	10.5(2.4)°	13.6°	0.55
14	19.9(3.0)°	18.9(2.9)°	23.2°	0.65
15	19.1(3.4)°	17.4(2.2)°	15.2°	0.68
16	12.5(2.2)°	13.3(2.9)°	15.0°	0.73
17	16(2.3)°	9.4(3.1)°	13.8°	0.71
18	14.8(2.8)°	12.9(1.5)°	14.4°	0.69
19	11.4(1.5)°	10.0(2.9)°	11.4°	0.69

Table 2. Thoracolumbar vertebral rotation measurements for one patient in Set B

Level	Aaro Mean(SD)	Symmetry angle	Symmetry ratio (S_r)
T1sup	-2.3(1.8)°	-4.9°	0.71
T1inf	-4.1(2.9)°	-5.6°	0.90
T2sup	-1.1(1.9)°	-1.4°	0.74
T2inf	-5.5(2.1)°	-7.5°	0.95
T3sup	-7.5(1.6)°	-6.3°	0.93
T3inf	-6.7(2.0)°	-8.2°	0.96
T4sup	-7.8(1.4)°	-9.4°	0.90
T4inf	-5.6(2.8)°	-10.4°	0.95
T5sup	-6.5(1.0)°	-6.4°	0.95
T5inf	-3.1(2.2)°	-7.1°	0.96
T6sup	-3.0(2.6)°	-5.0°	0.90
T6inf	2.7(1.8)°	-1.9°	0.92
T7sup	3.9(0.9)°	0.4°	0.93
T7inf	8.7(2.3)°	5.5°	0.93
T8sup	9.1(1.9)°	6.7°	0.93
T8inf	13.4(1.2)°	11.6°	0.93
T9sup	12.8(1.3)°	11.9°	0.92
T9inf	13.1(2.2)°	13.1°	0.96
T10sup	13.5(2.4)°	10.5°	0.89
T10inf	15.5(1.7)°	12.4°	0.92
T11sup	12.2(1.8)°	8.8°	0.83
T11inf	11.9(1.0)°	8.5°	0.91
T12sup	7.3(1.9)°	7.7°	0.93
T12inf	4.5(1.9)°	3.7°	0.97
L1sup	4.1(1.7)°	0.2°	0.95
L1inf	-3.1(1.4)°	-5.0°	0.97
L2sup	-6.5(1.5)°	-4.4°	0.96
L2inf	-6.7(1.7)°	-8.0°	0.98
L3sup	-5.3(1.4)°	-8.4°	0.99
L3inf	-7.7(1.6)°	-8.2°	0.92
L4sup	-6.3(2.0)°	-7.9°	0.96
L4inf	-5.8(2.3)°	-7.8°	0.96
L5sup	-9.0(2.8)°	-6.5°	0.92
L5inf	-8.2(1.9)°	-6.2°	0.90



(a) (b)

Figure 1. (a) CT image of rotated vertebrae in idiopathic scoliosis (b) thresholded image with region of interest defined

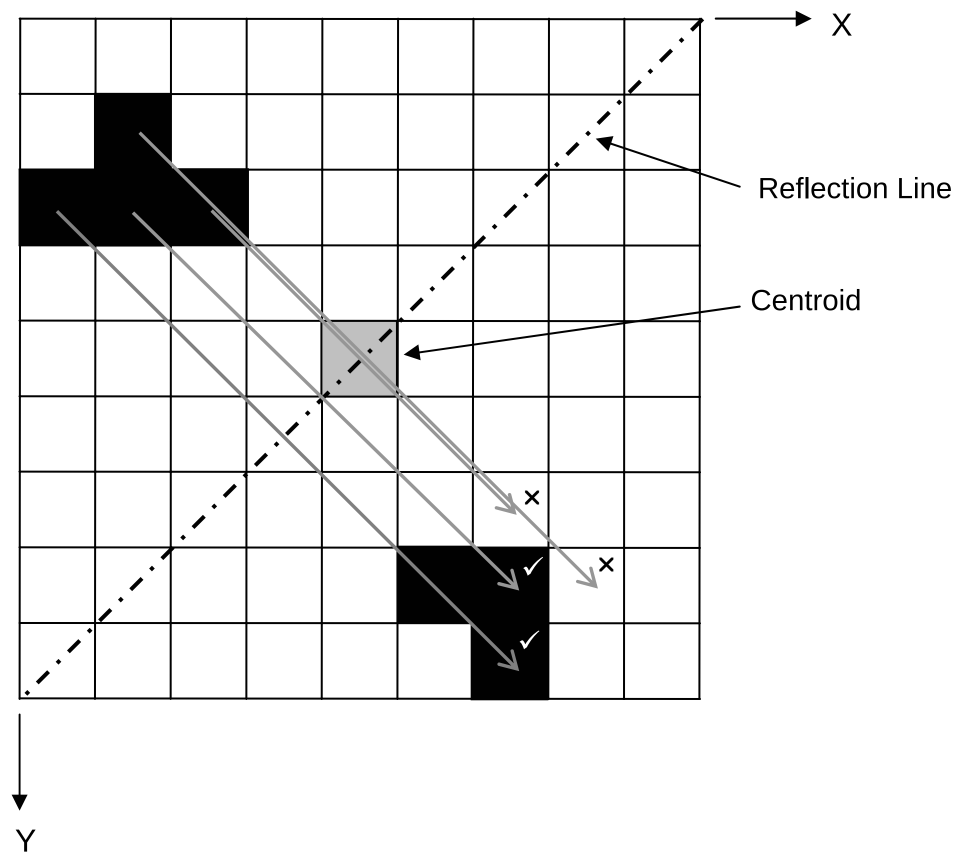


Figure 2. Mapping of pixels across reflection line to determine symmetry ratio

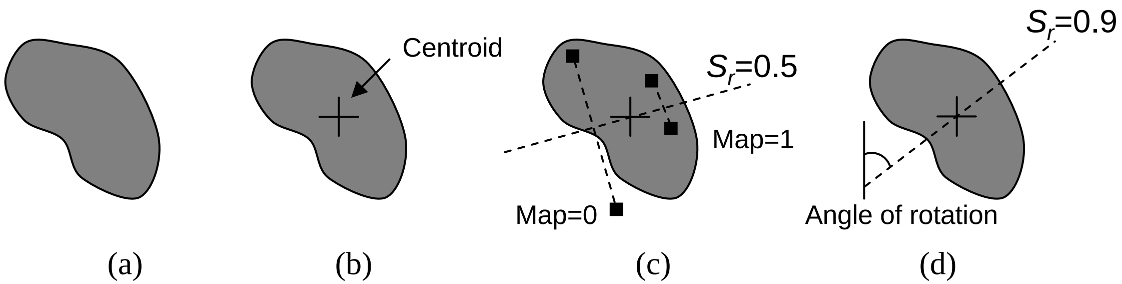


Figure 3. (a) arbitrary object in thresholded image (b) centroid located (c) symmetry mapping across reflection axis (d) axis of maximum symmetry defines rotation angle

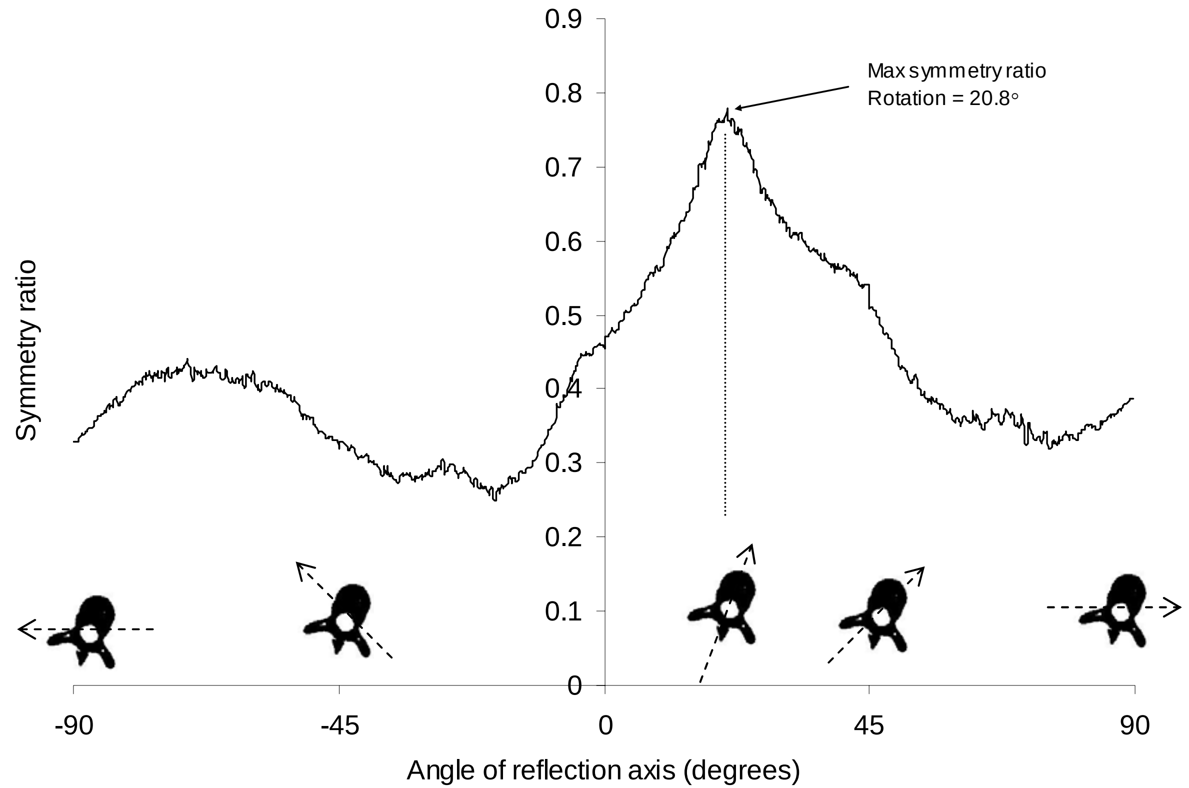


Figure 4. Variation of symmetry ratio with reflection line angle (for the vertebrae in Figure 1) showing axis of maximum symmetry at 20.8° rotation from the vertical

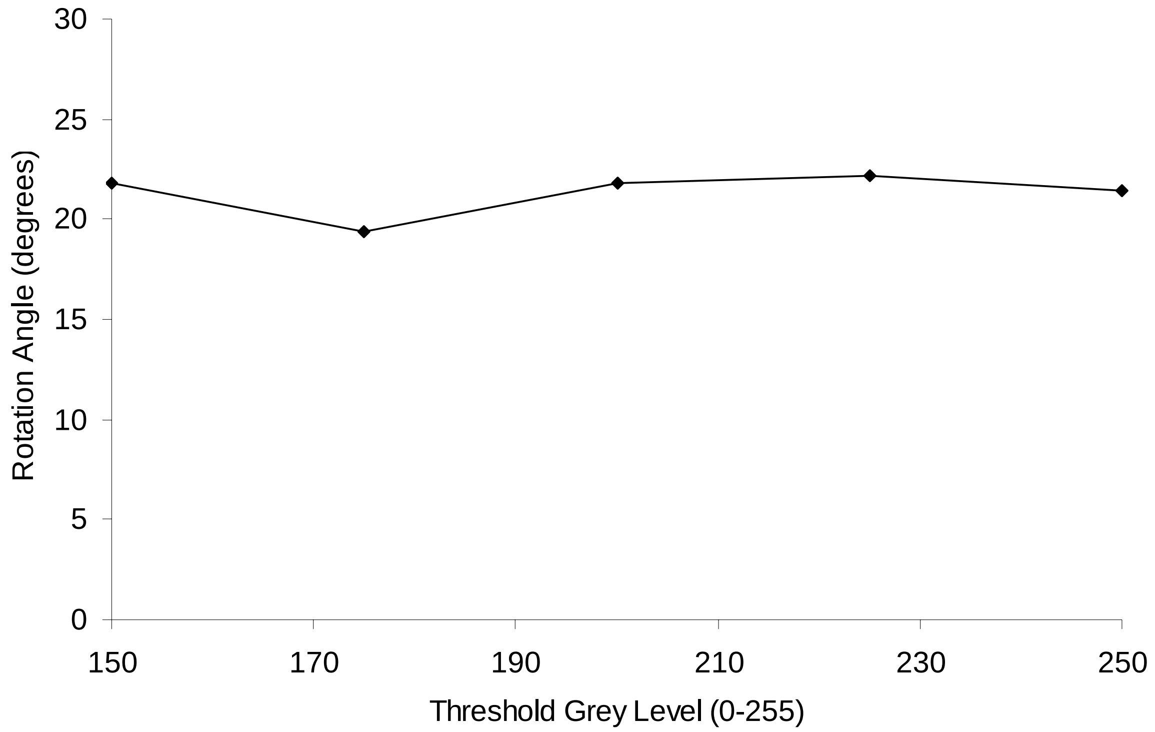


Figure 5. Sensitivity of symmetry ratio rotation measurement to changes in threshold grey level